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Opportunities and challenges in energy demand reduction for Canadian residential sector: A review

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ABSTRACT

Developing energy independent and sustainable communities has gained a high level of global interest in recent times. The Federal Sustainable Development Strategy for Canada (FSDS) has defined the addressing of climate change and the shrinking of the environmental footprint as priority themes in its sustainable development approach. In the pursuit of planning net-zero to net-positive community energy systems, reducing the energy demand of the residential buildings is the first priority, particularly as the residential sector accounts for 17% of the secondary energy use in Canada. Various technical, behavioural, and policy level interventions are available for reducing residential energy consumption. In this review, demand reduction interventions have been categorised as efficiency, saving and conservation measures. The benefits, limitations and challenges present in adopting those strategies are discussed for various regions in Canada. Even though there is an advanced level of knowledge available on energy demand reduction, the scattered information needs to be brought together to develop a combined and inclusive approach for residential demand management. Collected knowledge will inform decision makers engaged in the design of residential buildings and planning of sustainable communities to identify the interventions which can be implemented in a given locality. This review aims to address the above gaps through a comprehensive review on potential energy demand reduction methods, especially for Canada. The implications of the findings to Canadian residential energy sector as a whole are discussed in the final part of the review.

1. Introduction

With the global concern of climate change, much attention has been paid to anthropogenic greenhouse gas (GHG) emissions control. GHG emissions are a leading cause of climate change, producing adverse effects such as global warming, changing weather patterns and rising sea levels [1,2]. In 2015, the Government of Canada announced a new emission reduction target, promising to reduce the greenhouse gas (GHG) emissions by 30% by 2030, in comparison to the 2005 emission levels, in line with the United Nations climate change conference goals in Paris (COP21) [3,4]. This challenging target is planned to be met through controls and regulatory measures in oil and gas, electricity, and chemical sectors, as well as through provincial emission reductions [5].

The use of energy in its various forms plays a major role in GHG emissions, with the sector accounting for approximately 80% of the total GHG emissions within the country [6]. These emissions in the energy sector are mostly due to the use of fossil fuels in energy generation [6,7]. At a global level, buildings contribute to around 40% of the world's energy use [8]. Table 1 provides details on the energy use and the contribution made to overall GHG emissions by each economic sector in Canada. It is evident that the residential sector accounts for a significant portion of both energy use and emissions. Therefore, it is important to focus on this sector in the effort to mitigate the environmental and economic burdens of energy use.

By 2020, GHG emissions from Canadian residential buildings are expected to rise by 15% from the 2012 levels, an increase equivalent to 6 Mt CO_2eq[1] [9]. It is evident that reducing the energy demand of residential buildings can have a significant impact on the emissions and energy security of the communities. In Canada, the main energy end uses of the residential sector are space heating (63%), water heating (19%), appliances (12%), lighting (4%) and space cooling (1%), with around 80% of the total domestic energy being consumed by space and water heating [10]. Space cooling in Canadian residences too has increased from 22% to 46% of the occupied floor space from 1990 to 2013 [10]. This corresponds to an increase in the energy demand for residential space cooling by 95% during this period. In contrast, the energy use for space heating remained almost unchanged during the

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[1] Megatonnes of Carbon Dioxide equivalent.

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Table 1
Energy use and GHG emissions by sector.

Sector	Fraction of Canada's secondary energy use[a]	Contribution to national GHG emissions[b]
Residential	17%	14%
Commercial & institutional	10%	10%
Industrial	40%	36%
Transportation	30%	38%
Agriculture	3%	3%

[a] Based on 2013 data published by Natural Resources Canada [10].
[b] Based on 2013 data published by Natural Resources Canada [10].

period (increasing only marginally by 0.3%), and the increase in energy use for water heating was 28% [10]. The above mentioned residential energy demands are fulfilled mainly through natural gas (NG) and electricity, which together provide 82.5% of the total residential energy demand [10]. Other fuels such as propane, heating oil and wood cater a small portion of the total energy demand.

The net energy demand of residential buildings can be reduced via the means of technical and behavioural interventions [11,12]. Technical interventions can be implemented at the design or operational stages of residential buildings, while behavioural changes focus on establishing and improving environmentally conscious occupancy patterns. The concept of energy sustainable community planning acts as a pathway to long term emission reduction, energy security and energy independence for communities [13,14]. In order to develop such energy sustainable communities, managing the energy consumption in an efficient manner and reducing the energy consumption are vital necessities [14]. The "4 R's concept" developed by Robyn Wark and Jorge Marques of BC Hydro emphasises reducing demand as the first level in sustainable community energy planning, followed by reusing waste heat. The final levels of energy planning for sustainable communities focus on renewable heat and electricity generation [15]. Identifying interventions which can be applied in a particular locality will be beneficial in developing a framework for energy sustainable neighbourhoods.

In addition to economic and environmental advantages, efficient use of energy is closely linked with the integration of renewable technologies to the energy production [8]. With the reduced energy demand, it is easier to supply the remainder through renewables, and distributed generation systems which are highly compatible with RE sources such as wind and solar can be implemented [8].

The objective of this review is to identify and classify the energy demand reduction interventions applicable for the residential sector, thus bringing the dispersed knowledge on residential energy management together. The challenges in implementing demand reduction mechanisms are also discussed. The Canadian context in residential energy use and demand reduction is explored at length in the final section, to identify the strategies and requirements in developing energy sustainable communities in Canada. The compilation of information will be useful for decision makers and planners in developing sustainable and holistic strategies in reducing the energy demand, especially at community level.

2. Methodology

A multitude of interventions have been proposed and implemented all over the world to achieve the target of reducing energy demand [16–19]. In this review, these interventions have been categorised under the classification described in Table 2 as energy conservation, energy efficiency and energy saving measures [20]. The applications, challenges and limitations of each category are discussed in detail in the following sections.

This study aims to collect and compile the information to identify the essential components of demand side management for residential sector. The above definitions will be used in discussing demand reduction measures applicable to Canada, to analyse the present scenario and the benefits, needs and challenges associated with reducing residential energy consumption.

This study used keyword searches in related databases to collect required data. A similar approach was used by Heier et al. and Ruparathna et al. in conducting literature review studies [22,23]. "Compendex Engineering Village" and "Science Direct" databases were searched using keyword combinations of the terms "*energy demand reduction*", "*residential buildings*", "*energy conservation*", "*energy efficiency*", "*energy saving*" and "*passive buildings*". Articles published after year 2000 were prioritised in order to keep the information up-to-date.

The search results were further narrowed down by prioritising the articles from journals with high impact factors, which is a measure of how frequently that particular journal has been cited [24]. This strategy was based on the hypothesis that the impact factor provides means of ranking and comparing journals [25]. Journals with high impact factors thereby provide high quality literature for the purpose of the review. Publications from following journals listed in Table 3 with a five-year impact factor of 2.5 or above (as of August 2016) were selected based on this criterion.

In addition to the above sources, reports published by governmental and non-governmental organisations were used as references in obtaining statistical data and other information.

3. Improving energy efficiency

Energy efficient technologies which reduce the waste of energy in appliances in non-useful forms (such as heat and noise) have a positive influence on residential energy consumption. Improving the energy efficiency of household electrical appliances has been promoted as a strategy for reducing energy demand, thereby mitigating the harmful environmental impacts while also easing the secondary costs incurred by the consumers over the operational lifetime of the product [26,27].

3.1. Interventions for increasing energy efficiency

Within the Canadian residential sector, appliances and lighting are energy consumers and contributors to emissions [28,29]. The main electrical appliances used in Canadian households can be identified as refrigerators, freezers, dishwashers, clothes washers and dryers, in addition to the cooking equipment, air-conditioning equipment and consumer electronics [30]. Various efficient appliance and lighting technologies have been introduced to the residential consumer market over the years, such as LED and CFL lighting, refrigerators and freezers with improved compressor efficiency and insulation, automatic controllers in dryers with moisture sensors, and smart power bars in electronics [31]. In addition to efficiency improvements in the above listed appliances, the use of efficient technologies in HVAC system components (such as heating system, air conditioners and fans) can also result in considerable energy savings [32].

The efficiencies of household equipment increase with time as more advanced technologies permeate into the market. However, it has been noted that actual realised savings associated with the use of efficient appliance technologies are dependent on the propensity of the users to replace the aged equipment with newer models with enhanced efficiency [30]. Even if highly efficient technologies are available in the market, residential occupants may continue to use their outdated and less-efficient models without substituting them with advanced appliances. The time-to-replacement for a particular appliance is also important as the equipment performance deteriorates over time as it ages, leading to higher energy use [33]. The optimal time-to-replacement for appliances is governed by conflicting objectives related to

Table 2
Demand reduction intervention categories.

Category	Definition	Type of intervention
Energy efficiency	Maximising the useful energy output by minimising the waste, thereby reducing the required energy input [14] - Same consumption patterns may be maintained with a lower energy demand [20]	Technological – using appliances and technologies with improved efficiency Regulatory – adoption of efficiency standards [20]
Energy savings	Replacing active energy consuming activities through passive means [16,20]	Technological – materials, products or designs which replace an energy consuming service, incorporated in building design or retrofitting [21]
Energy conservation	Reducing the energy demand through conservation practices [11,20]	Behavioural – reducing energy use through changes in occupant behaviour Technological & regulatory – interventions intended to influence conservatory practices [11]

Table 3
Primary sources of published literature.

Journal	Impact factor
Energy	4.810
Renewable Energy	4.068
Applied Energy	6.222
Renewable and sustainable energy reviews	7.896
Energy and Buildings	3.666
Energy Policy	3.701
Energy Conversion and Management	4.631
Buildings and Environment	3.804

replacement cost and energy use. An example of this nature can be found in a study conducted on domestic refrigerator use in the United States by Kim et al. (2006) with the use of a life cycle optimisation model. The results of this study indicate that for a model time period of 35 years, the energy objective is optimised with a lifetime range of 2–7 years. In contrast, the economic cost objective is optimised with a service lifetime of 18 years [33].

In the Canadian context, the equipment replacement statistics indicate that in reality most household appliances are replaced only after the previous model has undergone failure [30]. The time-to-replacement varies based on the type of appliance, replacement cost, and rate of survival. According to Young, clothes washers and dryers were most likely to be replaced after 11–20 years of use, while the replacement time for dishwashers could be as low as five years, and refrigerators and freezers had a high probability of surviving beyond 20 years [30]. A 2015 study notes that energy savings of 11% can be achieved by replacing older refrigerators with a model of higher efficiency, and that households tend to vastly overestimate their lighting use while underestimating the HVAC load by 29% [34]. The effectiveness of energy efficient technologies also depends on the operational and maintenance practices adopted at the residential level. The recommendations provided by the National Renewable Energy Laboratory (NREL) of the US Department of Energy include regular cleaning, replacement of components which wear out, and the unplugging of equipment when not in use to prevent energy waste [35].

There is clear evidence that energy efficiency programmes can achieve significant energy savings and emissions reductions. It has been estimated that EU can obtain energy savings of 7% through the changeover to energy efficient household appliances [32]. In Canada, the estimated energy savings from all shipped appliances amounted to over 66 PJ[2] from year 1992 to 2011, with an average set of main household appliances consuming less than 2800 kWh per year (about 50% reduction from the energy consumed by the same in 1992) [36]. The Quadrennial Technology Review 2015 of the U.S. Department of Energy estimates that the use of ENERGY STAR® technologies would decrease the residential energy demand by 30%, in comparison to the maximum theoretical limit of saving which is 62% [37]. A Mexican study has indicated an estimated energy saving of 22,605 GWh as a result of government directed appliance energy efficiency programmes, leading to cumulative reduction of CO_2 emissions amounting to 15,087 Tg[3] for period of 25 years (from 1996 to 2021) [38].

3.2. Influence of socioeconomic factors and policy on consumer behaviour

Overall, the main factors influencing consumer behaviour with regards to equipment replacement tend to be income level, demographics, occupancy levels and patterns in households, availability of information, as well as the environmental attitude of the user [26,30]. When selecting appliances, the major characteristics influencing choice are “cost” and “quality” [26]. However, consumers are also influenced to a lesser extent by factors such as technical parameters, brand, energy consumption, aesthetics, safety and user-friendliness [26].

The policy instruments used in promoting energy efficiency can be categorised as fiscal instruments (taxes, subsidies and incentives), market mechanisms, regulatory policies (energy standards and labelling, building codes), voluntary agreements, research and development (R & D) policies, and policy processes (outreach programmes, consultation, information dissemination) [27,39].

Energy efficient standards and labelling where technologies are ranked based on their performance efficiency are among the most prominent schemes used in promoting the using of efficient technologies in the residential sector [40]. The consumers’ environmental response is chiefly based on the energy efficiency, and they obtain the information to make their purchasing decisions based on the energy labels [26]. At present, Canada uses the “*ENERGY STAR*” and “*EnerGuide*” labelling to indicate the energy efficiency characteristics of appliances, so as to enable the public to make informed decisions [31]. The EnerGuide ratings are assigned based on the annual energy consumption, and ENERGY STAR labels are incorporated to the ratings for the top performing models which meet the minimum technical specifications based on efficiency [41]. Among the criteria used in selecting appliances for ENERGY STAR label are contribution to energy savings, meeting the consumers’ feature and performance requirements, the ability to measure consumption and performance through testing [42]. However, these may vary based on the appliance or product. These schemes also provide online resources to consumers on assessing the potential savings through the replacement of older appliance models with new ones. Some financial incentive programmes such as tax incentives and energy rebates are used in various parts of Canada to motivate users to replace household appliances with Energy Star rated models [30,42]. It has been identified that in 2011, ENERGY STAR qualification was held by 67% of refrigerators, 79% percent of dishwashers, and 75% of clothes washers in Canada [36]. A study conducted in Germany indicates that the energy labels had a significant

[2] Peta Joules (equivalent to 10^{15} Joules).

[3] One million metric tonnes.

positive impact on the purchase of high efficiency appliances after their introduction, with the sales in the highest efficiency rated refrigerators rising from approximately 6–29% from 1994 to1999 [43]. The United States Environmental Protection Agency estimates that in 2013, the ENERGY STAR programme helped to reduce 380 billion kWh of energy use in 2013, and that since the inception of its home labelling programme in 1995, the total saving on energy costs for residential consumers have been over $ 4 billion, with a corresponding emissions reduction of 21 $MMTCO_2$[4] [44].

However, awareness on energy efficiency and knowledge to make informed decisions are key factors in determining consumer behaviour towards energy efficient appliances [26,45]. It has been suggested that the provision of information on energy consumption, water consumption, warranty, and customer support on the energy label could increase the effectiveness in their penetration among the public [26].

In addition to managing the consumer response, the supply side of appliances and equipment also needs to managed and regulated for optimising demand reduction via efficient technologies [27]. Tax incentives and subsidies provided to manufacturers and setting of minimum energy performance standards for equipment are used to promote the release of more efficient technologies into the market [27,40]. Providing the information on energy class labelling at sales venues and through local authorities during the registration of new residences can also be an effective strategy [46].

3.3. Limitations and challenges of increasing efficiency

The main barrier which stands in the way of penetration of energy efficient technologies is the prohibitive nature of the costs involved in purchasing energy efficient products [40]. Consumers tend to perceive cost as an extremely important element in making their purchase decisions, and in general, possess a bias towards immediate savings at the purchase point over potential long-term savings from energy demand reduction [26,40].

The high development costs which may discourage manufacturers from pursuing further efficient technologies can be offset through financial incentives and facilitation of technology transfer [47]. In the residential sector, the *principal agent problem* also acts as a barrier to the penetration of efficient technologies [27,48]. The landlords of rental accommodations may invest in cheaper and less efficient technological options, while the energy costs are incurred by the tenants [27]. The above issue can be addressed through regulatory measures, both by ensuring that all appliances in the market are above a threshold level of efficiency, and by imposing efficiency requirements for appliance selection in residential housing planning and design [48]. This aspect is addressed in some of the existing building energy codes [49].

The energy savings which can be achieved through the use of efficient technologies are subject to an upper limit due to a number of theoretical and practical reasons [50,51]. Technical reasons include the thermodynamic limit on the maximum efficiency achievable (e.g. Carnot efficiency), as well as technical limitations on the possible efficiency with the current technology available [51]. Even if there are technological means to achieve higher efficiencies in appliances, it might not be economical or commercially viable to implement these measures in the appliances released to the market, and the market trends may also play a part in determining what technologies and appliances are accepted by the consumers [51]. Due to the above factors, the potential of efficient appliance technologies in reducing the residential energy demand may reach a maximum point of saturation, particularly as the efficient technologies reach their practical limits. However, there is yet a potential for further improvement in terms of energy efficiency of residential end uses [37,52].

[4] Million metric tons of CO_2 equivalent.

4. Energy saving measures in residential buildings

Energy savings in residential buildings can be achieved via non-energy consuming (passive) interventions [16,53]. In this approach, interventions for reducing energy consumption can be implemented in the building design itself, or through the use of specific materials. These interventions attempt to reduce the net energy demand in residential buildings by facilitating natural heating, cooling, ventilation or lighting [16,53,54].

4.1. Technological initiatives and current practice

Space heating and cooling together account for 64% of the total residential energy consumption in Canada [10], and a significant impact could be made on the heating and cooling energy demand of buildings through modifications in their shape and orientation, envelope design, and shading [16,54,55]. The shape factor of a building and its orientation are decisive factors in determining the exposure of the façade [16,56]. Aksoy and Inalli (2009) conducted a study for Turkey, demonstrating that building orientation, shape factor, and insulation have a significant effect on energy consumption, with savings of 34–36% achievable by combining the optimal parameters for the above factors [19]. Florides et al. established that a lower area-to-volume ratio (compactness index) leads to better thermal performance, and that an elongated house leads to an increase of 8.2–26.7% in the annual heating load [56]. An optimal building envelope design can eliminate the need for additional infrastructure costs (for heating etc.) while improving the COP (coefficient of performance) of heat pumps [57].

The wall configuration is a critical factor in building energy demand reduction [16]. The heat transfer between the residence and the environment through the building envelope is directly dependent on the thermal conductivity [16]. By using techniques such as double walls with insulator materials, and optimising parameters such as window-to-wall ratio, the energy spent on heating and cooling can be reduced [16,56]. The type of roof and materials used also has an effect on the thermal conductivity and therefore the heating and cooling loads [56].

Some of the modern developments in low energy building design incorporates energy savings through the use of materials [58,59]. By using insulation which can trap heat and is opaque to solar radiation or capable of reflection, heat losses and overheating can be prevented (e.g. brick or concrete walls with thermal insulation from mineral wool or polystyrene) [58]. Phase change materials (PCM) which are capable of absorbing and storing heat energy can be used as a mean of passive thermal control in residential buildings [60,61]. Previous studies have demonstrated that energy savings of 5–20% can be gained from the use of PCM in residential buildings, depending on the local climatic conditions [62], and they can also be beneficial for load profile management by shifting the space thermal conditioning loads to off-peak times [60,63]. A study conducted in China indicates that a passive solar house provisioned with a water thermal storage wall can obtain an energy saving of 8.6% per annum [64]. It should be noted that in the case of insulation, the effectiveness reduces after a certain level as the insulation is increased [65].

Specific components such as windows and shading can be designed to save energy at building level. Glazed windows, overhangs to minimise the direct solar radiation entering, and shading devices are all technologies used to control the movement of heat between the building and the environment [16,56]. The positioning of the building itself can be used to achieve energy savings via self-shading, or by utilising the shading available from neighbourhood buildings [16]. The window shape, size, orientation and positioning can impact the amount of artificial lighting required within a residence [66,67].

Natural ventilation techniques such as buildings using stack effect and solar chimneys reduce the need for active cooling and heating, while increasing thermal comfort for the occupants [16,54].

Furthermore, technologies such as trombe walls and passive solar roofs which have the ability to trap solar energy can also contribute to reducing the residential demand via passive means [54,59].

4.2. Level of penetration and potential for improvement

The above-mentioned measures are not an exhaustive list of the available interventions for energy saving in residential building design. As demonstrated above, the use of passive energy saving technologies in the building design phase can generate considerable energy savings in their operational lifetime. However, the increased initial investment requirements may act as a barrier to their widespread utilisation [68,69]. The integration of such interventions in the residential building design leads to a significant increase in the cost and workload of the construction, and limits the use of aesthetically appealing design styles, while delivering no tangible benefit to the developers [68]. Due to this, there may be reluctance in adopting these measures among designers, developers, and contractors. However, residential buildings with lower energy requirements can gain a higher market value, thus benefitting the developers in the long-term [65]. Studies have indicated that home buyers may be willing to pay as much as 9% higher premium prices for green-rated housing [70]. It can also be reasoned that when considering the occupational life of residential buildings, the cost incurred by the implementation of passive energy saving technologies is negated by the cost saving due to the elimination of active mechanical systems [59].

While the use of natural lighting during the daytime is a widely used method to reduce lighting energy demand, attention must be paid to the increased cooling loads in hotter climates due to increased exposure to daylights [71]. Window glazing and shadings present another facet of this issue, in that while thermal load savings can be achieved by glazing, the lighting requirements may increase due to it [16,56]. A balance needs to be achieved between these conflicting requirements in order to optimise building energy performance.

The possibility of controlling solar heat gains and losses through the site location has important potential in developing residential neighbourhoods. Designing the layout of the neighbourhood and its open spaces in a manner that facilitates maximum utilisation of solar radiation and allows daylight access will increase the energy efficiency of the total system [16,53].

The life cycle impacts of energy saving features should be taken into account when incorporating them into residential building design. The energy use, emissions, and other impacts due to a technology or an energy saving feature should be considered throughout its life cycle processes from raw material extraction, manufacturing, construction, to eventual decommissioning at end-of-life [72]. A study by Lollini et al. concluded that the increased environmental costs of the use of insulating materials (in terms of energy and emissions) will be paid back in a relatively short duration, considering a building life span of 60 years [65]. A Dutch study conducted on nearly-zero energy buildings concluded that while low-energy intensity buildings are typically associated with high life cycle costs, this can be offset when the additional benefits are translated to economic terms. The higher renting value and improved indoor climate of the buildings, and positive public relations contribute to this favourable economic effect [73]. However, further investigations are necessary on quantifying the life cycle impacts of energy saving technologies and designs in building construction.

4.3. Standards and regulatory measures

Energy saving building design has been promoted in many parts of the world at regulatory level with building energy codes (BEC) and standards [68,74,75]. These codes cover a range of aspects including the building envelope, lighting and HVAC systems, electric power systems and water heating, and can be instrumental in long-term demand reduction for the residential sector [49]. Building energy codes have been successful in reducing the energy demand with savings of 6% in Southern European countries and up to 22% in Netherlands and Germany [76]. The International Energy Agency (IEA) specifies that the effectiveness of BECs depend on being mandatory and enforced, and that they should extend to all types of building in construction, extension and renovation, and be based on overall performance with the minimum levels set as per best available technologies [75].

BECs have been categorised into two main types as *performance based* and *prescriptive* [49]. Timmons et al. (2016) contend that the use of prescriptive building energy codes (which define minimum performance levels for individual building components) in building energy decarbonisation (through conservation of energy and replacement with carbon free sources) is not the optimal solution under a cost perspective. Their reasoning is that such codes do not allow flexibility to the developers to make the investment decisions in balancing the renewable energies and energy saving in the most cost-effective manner [57]. In the same study, it is proposed that carbon taxes and building emissions standards are more effective in achieving this goal [57]. In summary, prescriptive BECs limit the designers and developers [49]. Performance based codes, on the other hand, are projected to be more suitable as they stipulate energy performance requirements for building designs, and the overall consumption of different load types such as heating, cooling, ventilation and lighting [49,75]. At present, this type of BEC is utilised only by Denmark, France and Tunisia [75]. Zero-energy buildings are also an emerging concept under BECs [49]. Planning, effective implementation, monitoring and tracking of compliance, and evaluation to carry out necessary updates are all integral components of BEC policies [76].

Furthermore, passive energy saving techniques have been incorporated to green building rating tools such as BREEAM, LEED and CASBEE as feasible instruments in mitigating environmental impacts of buildings [49,53]. Certification and incentives provided for buildings are also used as measures to promote energy savings [49,77].

A concern raised with regards to the implementation of energy efficient and energy saving measures, particularly with regards to buildings, is that the actual savings generated through such interventions are less than the expected value due to the rebound effects. Under this, improvements in energy efficiency and savings can lead to an elevation in energy use by the populace, instead of resulting in an overall reduction [69]. In other words, residents tend be more carefree in their usage patterns thus using more energy, when they operate under the perception that less energy is being consumed due to energy saving measures and high efficiency technologies. Therefore, behavioural factors are also an important aspect in residential energy demand management.

5. Energy conservation

The concept of conservation applies to user-centered interventions for reducing the energy use of a residence, through methods which eliminate the non-essential utilisation of energy. Demand reduction can further be achieved by means of engaging in conservation practices, which by and large fall under the category of behavioural interventions.

5.1. Conservation and its impact on demand reduction

Studies indicate that a demand reduction of as much as 10–20% can be obtained through changes in behavioural patterns [78]. Ouyang and Hokao established through a study conducted in China that improvements made in occupant behaviour can save over 10% in electricity demand [79]. While conservation is interrelated with the previously discussed efficiency and savings choices, the social aspects and the ways of promoting energy-conscious consumption behaviours should also need to be studied in effective demand management.

Energy conserving behaviours can be in many forms, such as the

Table 4
Challenges for the penetration of energy demand reduction interventions.

Challenges	Potential solutions
Lack of access to financing	Providing taxes, subsidies and other financial incentives [27,39], loans and other similar capital funding mechanisms [93]
Lack of public awareness and consumer preferences	Comprehensive energy labelling schemes [27]; provision of outreach programmes and consultation
Lack of motivation for implementing demand reduction measures and split incentives	Regulations for specifying minimum energy efficiency requirements [48]; informing developers on the prospect of obtaining higher prices on "green rated" residences [70]
Inadequate price signals	Setting prices to reflect the real-time costs; integrating life cycle thinking for impact and cost assessment when setting energy prices [92]; setting utility prices to encourage energy conserving behaviour and efficient practices; dynamic pricing for time-differentiated energy use [94]; Incentives approach for peak demand reduction [88]
Lack of product and service availability	Motivating R & D in energy demand reduction interventions; incentivising market adoption of energy efficient and saving products through regulatory and financial interventions [27,40]
Institutional and regulatory barriers	Use of performance based building energy codes while integrating energy demand reduction into governmental policy making [49]

switching-off of unnecessary lights and electronic devices, adjustment of room temperature levels at night or in unoccupied spaces, using the washers and dryers only with a full load to reduce the usage frequency, and unplugging of devices when not in use [32,80]. Inefficient behaviour can result in significant wastage of energy in a residence, for example, with the standby consumption of the devices. It has been estimated that standby consumption (where electricity is used up by appliances in their idle state when not in use) accounts for 10.7% of the total household consumption in Australia, 7.3% in Japan and 10% in the Chinese urban sector [27,79].

In addition to the behavioural aspects, technological (physical) interventions can also play a role in energy conservation. The provision of smart control systems, automatic switches and energy meters on appliances are examples of such interventions which can promote and facilitate energy conservation [80–83]. Smart meters are another facet of the information factor in conservation, where the users are allowed an opportunity to identify the details regarding their energy use. Providing direct feedback to the users on their energy consumption through means such as meters or real-time displays can generate savings around 5–15% [84]. Direct-load-control systems can be used to turn off high energy consuming appliances such as A/C units for a period of time to save energy [83].

5.2. Effects of occupant behaviour and promoting energy conservation

Individual choices of the consumers can largely affect how much energy is consumed in residences, and therefore perceptions and knowledge plays a great role in managing domestic energy demand [85]. Chen et al. concluded that behavioural aspects accounted for 25–58% of the variation found in HVAC related energy use between the users in the 75th percentile and those in the 25th percentile [34]. The behaviour of individual households with regards to energy conservation can vary based on factors such as income, socio-cultural demographics and even the availability of free time [79]. Low cost-low skill behaviours are more likely to be adopted as habitual practices for energy conservation by households [86].

The attitude of the consumers on conservation depends on the costs, the effort involved, and the effect on their convenience [82]. Improving energy conservation by informing the public is more effective when the required changes do not have a significant negative impact on the finances or the convenience and comfort of the users [82]. It may also be necessary to tailor the provided information to suit the specific requirements of a particular demographic. In addition to providing information on energy saving and efficient energy use, feedback on energy use can also be helpful in promoting conservation behaviours among residential consumers [82]. Economic incentives in the form of taxes and subsidies on consumption influences consumer behaviour [81].

Countries such as Sweden have adopted information-focused programmes aimed towards the promotion of conservation practices [81,87]. As price is one of the key factors influencing the behaviour of users, time-of-use pricing which reflects peak and off-peak times can also be used in managing demand, and so has been adopted in some European countries [83]. A 2016 Swedish study suggests that real-time pricing delivers economic benefits to the users even without substantial changes in their consumption patterns [87]. Residential energy demand is considered to be mostly inelastic in nature [88,89]. Recent studies suggest that the price elasticity of demand relies on strength of the price signals. The increase in price should be significant enough to have a noticeable economic impact on the residential consumers in order to promote a change in the level of consumption [89].

Occupant characteristics also determine the overall energy performance of a residence. The results of a study by Kavousian et al. indicates that households which have a head of household with higher education were more efficient by a factor of 1.3%, which is a result of the use of energy saving and efficient technologies as well as lifestyle choices [90]. The mix of technical, social and economic factors which influence the management of residential demand calls for multidisciplinary studies to improve the overall residential energy demand profile [82].

6. Energy demand reduction strategies for Canada

Canada is composed of several different regions with varying climatic, economic and social conditions. In adapting demand reduction interventions and developing strategies for residential communities, it is important to take local conditions into account, so as to select the best alternatives and develop standards and codes accordingly [91].

The challenges discussed in the previous sections need to be addressed in developing demand reduction strategies for Canada. Barriers to the penetration of energy demand reduction strategies which cause an efficiency gap have been identified through a study conducted on demand side management potential for Canada [92]. Some of these challenges and potential solutions that can mitigate the issues have been summarised in Table 4, based on the findings of the review. It is evident that regulatory interventions and dissemination of information and guidance to developers and general public are critical factors in ensuring widespread acceptance of demand reduction strategies.

6.1. Current status of residential energy use

The total household energy use in Canada was 1425,185 terajoules (TJ) for the year 2011. The overall energy consumption intensity of smaller households was found to be higher, with households having less than 55 m^2 of heated space consuming 1.09 GJ/m^2 as opposed to 0.55 GJ/m^2 for those above 231 m^2 of heated floor space [12]. Natural Resources Canada has identified possible contributors to this trend of

smaller houses with less heated space having higher energy intensity. One possible reason is that the same set of appliances (such as refrigerators and clothes washers and driers) are being used in all types of households as necessities regardless of dwelling size, leading to greater impact per square metre for a smaller dwelling. Moreover, it has been identified that larger houses have generally been constructed after 1980s in Canada, and these constructions are more energy efficient [95]. A noticeable trend is the rising propensity to air-condition Canadian homes. The energy consumed in space cooling increased by 68% in the period between 1990 and 2009 [29].

Residential energy demand patterns are subject to variations based on the weather, particularly in the case of heating and cooling loads [7]. Energy efficient and conserving interventions (such as the use of CFLs, cold wash of laundry and turning off of appliances when not in use) as well as building retrofits (insulation, roof and window configuration etc.) have a considerable level of penetration within the Canadian residential sector. According to 2011 data, it is estimated that, 82% of the households engaged in at least one energy efficient or conservation intervention, while 37% of homeowners with their own residence had made an energy saving retrofit [12]. The National Energy Code of Canada for Buildings 2015 provides guidelines with regards to aspects such as lighting, HVAC system, building envelope, service water heating etc. [96]. New buildings constructed as per the code are expected to be 27% more efficient in comparison to the 1997 levels [97]. The National Energy Board of Canada has projected that in the period between 2016 and 2040, the energy use per one square metre of residential floor space will reduce by 0.7% annually, due to the increased use of efficient technologies, improved building envelope construction practices, and the advent of new energy standards [7].

6.2. Regional effects

There are varying regional requirements across Canada in the context of residential energy demand reduction, due to the differing climatic conditions, energy consumption patterns and emissions targets. Therefore, the interventions as well as the decision making strategies should be adapted to the local needs. A 2016 study has identified that at household level, the lowest GHG emissions on average are in Montreal, Quebec, followed by Vancouver British Columbia [98]. The possible reasons for this is the lower grid emissions factors in the two provinces due to the higher presence of renewables in their energy mix [99]. In the same line, the provinces with a higher reliance on fossil fuels have higher GHG emission intensities per household, with Edmonton and Calgary leading [98]. The variation in residential energy intensity across the provinces and the provincial emissions targets are detailed in Table 5. It can be seen that all Canadian provinces have ambitious emissions reduction targets, which are expected to be met within the current decade.

The climatic conditions of a region affect the performance of heating, cooling and lighting systems, and the effectiveness of the demand reduction interventions applied on them. While larger and more exposed fenestrations may reduce the lighting loads of a building, it may also lead to an increase in the heating requirements [110]. Canada is composed of seven climatic zones, ranging from warm and humid conditions to frigid Arctic climates based on the seasonal variations and the geographic locations. The subarctic regions are subject to long cool summers and short cool winters, while prairies experience extreme shifts with cold winters and hot, dry summers [111]. With this climatic setup, it is necessary to adapt the demand reduction interventions to the local conditions to ensure their effectiveness. The social and demographic conditions of the locales are also important in defining the regional strategies, as discussed in the previous sections.

While the colder climates have a higher need for heating related interventions and retrofits, provinces with warmer climates also have the need of regulating and facilitating demand management in cooling aspects. For *ENERGY STAR* certification of fenestration products such as windows, doors, and skylights, Canada has been divided into three climate zones, where zone 1 is the warmest and zone 3 is the coldest [112]. Product selection needs to be based on climate zone in which the residential building is located. The defining of these zones is done considering the heating-degree day (HDD) value. Some products may be certified for more than one zone. If the residence is located at a higher elevation than the area surrounding it, a product rated for a zone one level colder will be more suitable [112].

Many opportunities exist for promoting energy demand reduction at provincial, municipal and community level. Establishing legislative changes and creating capital funds to finance effective measures such as building retrofits can be effective mechanisms [113]. There is a multitude of financial incentives, grants and other programmes available at the federal, provincial and organisational levels to promote residential energy efficiency and savings [114]. In the residential sector, a considerable portion of the interventions are in the form of rebates intended to incentivise the use of efficient and energy saving technologies [115]. However, the process involved with this type of programmes may be time-consuming and effort intensive [115]. Voluntary programmes are used by all Canadian provinces and territories to promote the adoption of efficient and energy saving technologies. However, it can be noted that these programmes are discrete, and at times arbitrary. There is no overall guiding mechanism

Table 5
Residential energy intensity and emissions targets by province.

Region	Province	Annual household energy use (GJ)[a]	Emissions targets
Atlantic region	Newfoundland & Labrador	111	Reduce emissions by 10% below 1990 levels by 2020 and 70–85% below 2001 levels by 2050 [100]
	Prince Edward Island	142	Reduce emissions by 10% below 1990 levels by 2020 [101]
	Nova Scotia	101	Reduce emissions at least by 10% below 1990 levels by 2020 [102]
	New Brunswick	92	Reduce emissions by 10% below 1990 levels by 2020, and by 75–80% below 2011 levels by 2050 [103]
Central Canada	Quebec	95	Reduce emissions by 20% below 1990 levels by 2020 [104]
	Ontario	107	Reduce emissions by 15% below 1990 levels by 2020, followed by 37% reduction in 2030 and 80% in 2050 [105]
Prairie Provinces	Manitoba	98	Reduce emissions by 1/3 over 2005 levels by 2030, by half in 2050, and be carbon neutral by 2080 [106]
	Saskatchewan	110	20% reduction of emissions below 2006 levels by 2020 [107]
	Alberta	130	14% reduction in emissions by 2050 compared to 2005 levels (50% below business as usual scenario) [108]
West Coast	British Columbia	99	33% reduction of the 2007 GHG emission levels by 2020, and 80% by 2050 [109]

[a] Based on 2011 data published by Statistics Canada [12].

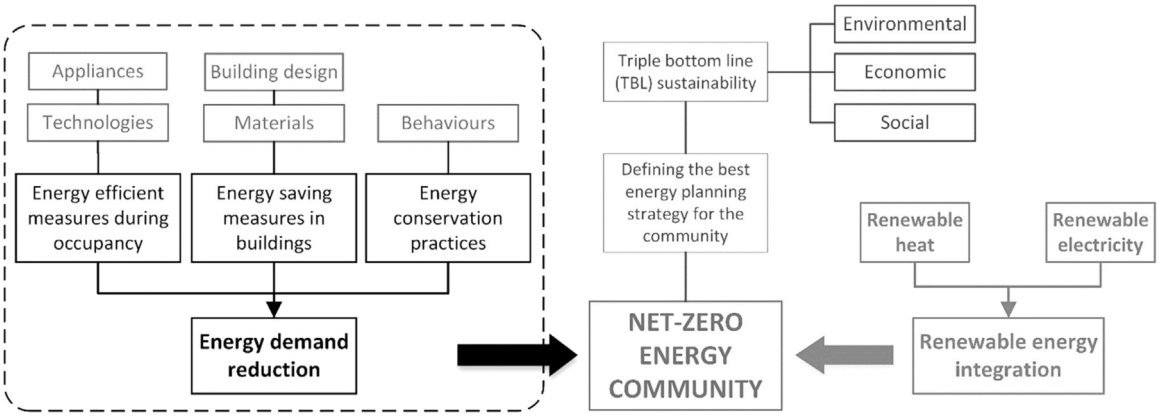

Fig. 1. Net-zero energy community planning.

or rationale followed in setting these programmes. A report on British Columbia (BC) efficiency requirements by the Pacific Institute for Climate Solutions (PICS) recommends that defining a net-zero target date for new buildings, creating a roadmap to achieve such targets, and developing performance assessment mechanisms for new constructions would serve the climate goals of the province [116]. This thinking is applicable to all parts of Canada, and creates a need for clearly defined approaches with comprehensive performance-based codes aligned with provincial and federal energy goals.

6.3. Developing a combined demand reduction strategy

Residential energy demand reduction needs to be considered at three major levels; namely decision making, design and development, and occupancy [117]. It is essential that the policy makers and other stakeholders are engaged in an inclusive approach in combining energy efficiency, energy saving and energy conservation methods, to develop an overall framework for reducing residential energy consumption instead of taking scattered and disconnected measures.

The decision makers hold a key role in popularising the demand reduction measures through financial and regulatory interventions. As previously discussed, energy demand is highly price sensitive. Conservation behaviours and the incorporation of energy efficient and saving technologies can be promoted by discouraging increased energy consumption through higher energy prices. Financial incentives in the form of subsidies and tax breaks for energy efficient and saving measures, as well as deterrents in the form of increased environmental taxes on less efficient technologies, can also be used as means of inducing demand reduction. Policy instruments play an important part in practically realising the potential of demand reduction measures, and in overcoming barriers such as the unavailability of funds, lack of incentives, and the information gap [118]. This effort needs to be extended beyond the currently existing building codes and separate incentive programmes, and should be planned in line with the federal energy targets incorporating regulations and policy instruments, financial incentives, and informative endeavours [118].

Community designers and planners as well as residential building developers are involved in the development stage. As discussed by Stephen and Stephen, developers are instrumental to reducing the operational energy consumption of buildings through the incorporation of energy saving technologies into the building design, such as insulation and building envelope design [117]. The site selection and layout of a residential community is also integral in reducing its energy use via passive means [16]. Therefore, demand reduction strategies need to be considered by both the urban planners and building developers in the project planning stage of a residential community. A combined framework as mentioned above would also serve to guide the planners and developers.

In the occupancy stage, the main impacts on energy demand reduction would be based on the users' willingness to invest in energy efficient appliances and engage in energy conserving behaviours [117]. The informing component of an overall demand reduction framework and associated financial incentives can make a significant impact on these aspects.

7. Sustainable community development

The net-zero energy (NZE) community concept is an extension of the net-zero building concept. The definition provided by the National Renewable Energy Laboratory (NREL) of the US Department of Energy states that in NZE communities the reduced energy demand of a community is provided through renewable energy (RE) sources (which are primarily located on-site) [119]. These community energy systems may or may not be grid connected, and in the case of grid-connectivity, the central utility grid is used for energy balance in supplying power at low RE production times, and absorbing any excess RE production. [119] Net-zero communities can be of different scales, from residential neighbourhoods and campuses to islands [120,121]. Net-zero or net-positive community planning is especially important in the context of remote communities where grid connectivity is difficult and costly [122,123]. For Canadian remote communities, this concept can deliver long term energy security and energy independence, leading to economic and social development. Fig. 1 depicts the aspects involved in planning NZE communities. In order to achieve the NZE concept, it is imperative to increase energy efficiency and reduce the energy demand significantly [119].

To achieve maximum benefit and true sustainability for the community, it is necessary to optimise both demand and supply sides of its energy system for the local environment under triple bottom line (TBL) objectives pertaining to economic, environmental and social aspects [124–126]. This optimisation of demand reduction needs to consider not only the energy use in a community, but also the costs, environmental impacts, and social welfare of energy use and potential interventions [73,127]. The economic and environmental burdens of energy use need to be compared with the potential benefits of demand reduction interventions. A simple example for this was discussed in the efficient technology section, where it was noted that improving the efficiency of appliance may not make commercial sense beyond a certain point, when the additional costs start outweighing the benefits. Moreover, the reduction of direct emissions during the operational phase of buildings need to be considered together with the life cycle environmental and social impacts of implementing any technological interventions in analysing the costs and benefits. In developing an optimised model for reducing community energy demand, a multi-stakeholder perspective needs to be adopted, as the economic, environmental and social benefits and burdens are shared by stakeholders at

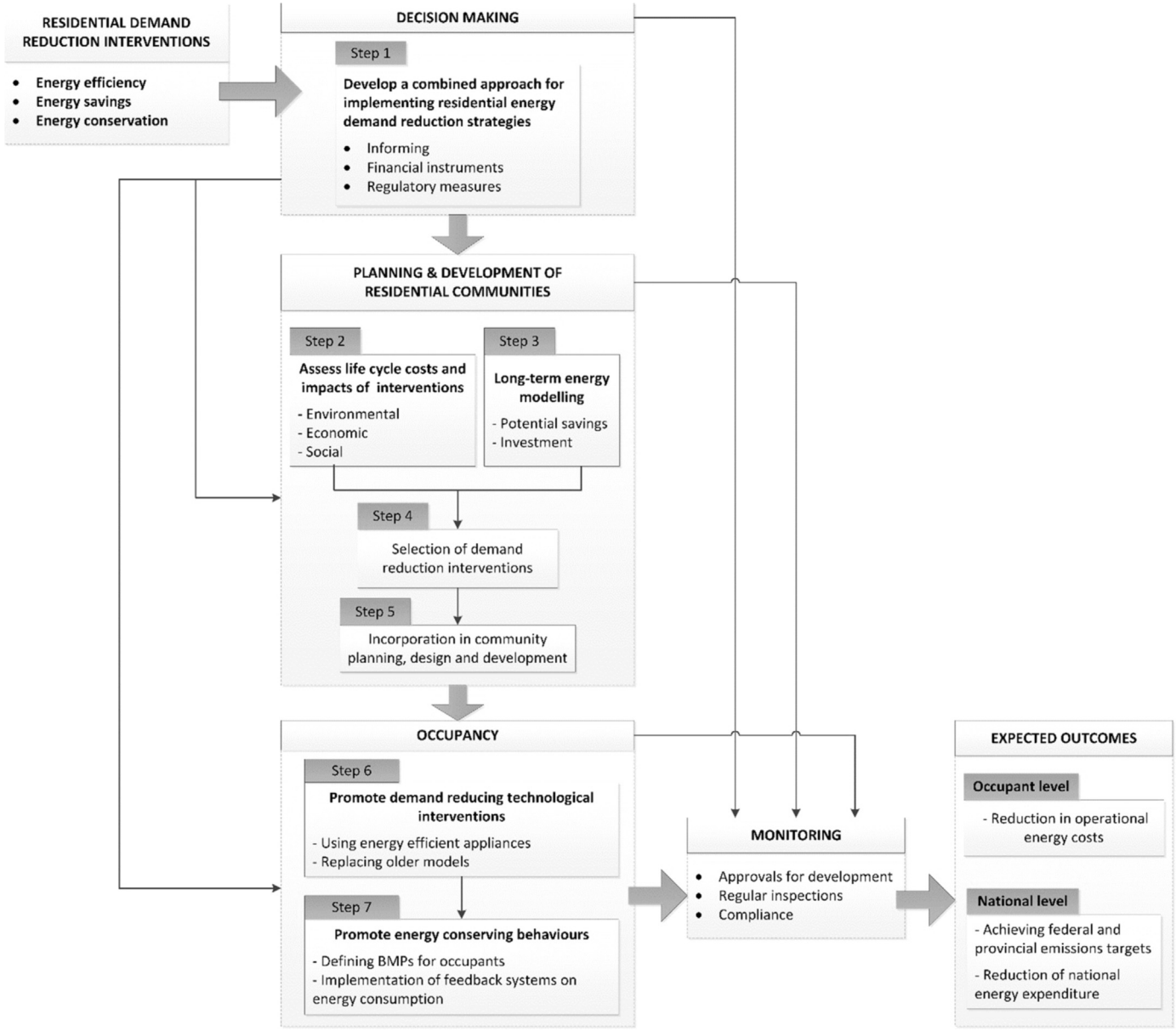

Fig. 2. Residential energy demand reduction approach.

all levels. In addition, stakeholder acceptance and support are vital to the success of a demand reduction strategy.

7.1. Impact assessment and long term planning

To achieve true sustainability via net-zero communities, it is necessary to look at the life cycle costs and impacts of the technologies used [117,128,129]. Life cycle thinking in the energy consumption of residential sector can have two aspects; the impacts in the building life cycle considering the construction, operational and end of life phases, and the life cycle impacts of the demand reduction interventions themselves. During this review, it was noted that there is a relative lack of studies focused on the life cycle costs and impacts of demand side management strategies at the residential level. This life cycle thinking should moreover be extended to the next phases in sustainable community planning, in incorporating renewable energies and heat recovery techniques to community energy systems. Additional factors such as thermal comfort and human health impacts are important considerations in the study of residential building energy systems [69]. Energy demand reduction measures can be implemented for thermal and electric end uses, and can be prioritised based on the potential savings. However, savings in the terms of energy does not necessarily correlate to a corresponding reduction in GHG emissions, and furthermore, the cost could be prohibitive in certain cases [130]. Therefore, it is vital to consider all the life cycle impacts and costs of an intervention before selecting a strategy. The success in incorporating demand reduction measures in residential sector also depends on the social acceptability of the proposed measures which depends on the stakeholder perspective.

Evaluating the effectiveness of demand reduction measures in terms of the cost and effort involved is important in selecting the most suitable interventions in the context of a given locality. Some interventions may come with a high price tag, but the benefits may be limited in comparison [131]. Long-term energy modelling can be employed to determine the effects and economic impacts of demand reduction interventions [131,132]. The impact of technological interventions as well as occupant behaviour can be evaluated with different modelling techniques [132]. The residential consumption varies based on the population, number of households, income levels, electricity and fuel prices as well as the weather conditions [133]. Energy modelling is

useful for selecting the best strategies when planning and developing residential communities, and can take a scenario-based or an optimisation approach. Optimisation of residential building energy systems is done with techniques such as mathematical programming, heuristics and artificial neural networks, and a number of software tools such as TRNSYS, DOE-2 and EnergyPlus are used in building energy simulations for evaluating energy efficiency [128]. In certain instances, relatively simple behavioural changes such as changing the thermostat settings at night can have a similar or larger effect to the more costly and effort-intensive appliance replacements [131]. The demand and emissions reductions which can be achieved per a dollar invested in interventions can be a valuable measure in assessing the suitability of an intervention. Bayesian networks are another approach that can be used in investigating the causality of a demand reduction model and evaluate its successful implementation [134].

The approach illustrated in Fig. 2 was outlined based on the findings of this review in developing a sustainable combined demand reduction strategy with consideration for the project planning and life cycle of residential communities. The importance of information and guidance in implementing energy demand reduction measures in the residential sector was a recurring theme throughout this review. Therefore, the defining and dissemination of best management practices (BMP) for residential sector on managing energy demand is crucial.

7.2. Other factors

While this review focuses mainly on reducing the operational energy use of residential buildings, the construction stage also plays a critical role in the overall energy consumption of residential sector, and therefore should be taken into consideration when planning sustainable communities [117]. The construction and operational costs of low energy residences need to be further studied in defining the optimal models for energy demand management for residential neighbourhoods [69]. The embodied energy of the residential buildings and the user-transport requirements play a large role in residential energy consumption [117]. While demand side management for reducing residential energy demand is a necessary first step in the path to sustainable communities, much more work needs to be done in the terms of optimising community energy system performance. The replacement of conventional energy sources for heating and electricity demand with renewable energy sources, as well as recovery of waste heat are areas which need to be explored [15,57]. The replacement of actively energy consuming devices with less energy consuming alternative (e.g. air conditioners with mechanical ventilators) is also an option to be studied further.

8. Conclusions

There are numerous technologies and behavioural interventions which can be utilised in demand management. While the use of these measures can create a considerable impact on reducing the residential energy use, there are many factors impeding the diffusion of energy efficient and energy saving interventions in the residential sector, thus creating an “efficiency gap” between the realised and theoretical optimal levels of efficiency in actual practice [134,135]. Managing the developer and consumer behaviour is a critical aspect in solving the issues related to this. Economic incentives can aid in the process to promote efficient technologies, energy saving designs, and energy-conscious practices in the residential sector. However, a comprehensive framework encompassing the decision making, design and occupancy of residential communities is necessary in realising the full potential of energy demand reduction interventions. This also acts as a first step in planning energy sustainable communities.

Long-term energy modelling is helpful in determining the effectiveness and potential costs and benefits of demand reduction interventions. The life cycle costs and impacts aspect should be a deciding factor in selecting the interventions for a residential community. When selecting interventions for demand reduction, it should be studied whether the cost and effort expended is worth the expected outcomes.

The climatic conditions greatly vary across different regions of Canada. Due to this, demand reduction interventions need to be regionally acceptable for maximum effectiveness. Information as well as regulatory and policy level measures play a vital role in managing residential energy consumption. Developing energy standards for residential neighbourhoods and defining BMPs are tools which can help in this. A combined demand reduction mechanism which takes a multi-stakeholder perspective and considers all levels of demand management in the residential sector will help in streamlining the efforts made in this regard. Canada can benefit from a comprehensive residential demand management strategy which incorporates all of the above discussed aspects, especially when planning neighbourhood communities. Reducing energy demand acts as the initial phase of developing sustainable net-zero energy communities. Therefore, an integrated community-level demand reduction and management strategy will aid decision makers, planners, and developers in setting up sustainable and energy secure communities in the future.

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